Exploring the relationship between adolescent biological maturation, physical activity, and sedentary behaviour: A systematic review and narrative synthesis

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Context: Across adolescence there is a notable decline in physical activity in boys and girls. Maturational timing may be a risk factor for disengagement from physical activity and increased sedentary behaviours during adolescence.

Objective: This systematic review aimed to summarize literature that examined the relationship between maturational timing, physical activity and sedentary behaviour in adolescents.

Methods: Six electronic databases were searched for articles that assessed biological maturation and physical activity (including sports participation and active transportation) or sedentary behaviours in adolescents. Two reviewers conducted title, abstract, and full-text screening, reference and forward citation searches. Included articles were evaluated for quality using a standardized tool. A narrative synthesis was used to analyse the findings due to the heterogeneity of the studies.

Results: Searches yielded 78 articles (64 unique studies) that met the inclusion criteria, representing 242,316 participants (153,179 unique). Studies ranged from 30.0% (low) to 91.7% (high) in quality. An inverse relationship between maturational timing and physical activity (in 50% and 60% of studies in boys and girls, respectively) and a positive relationship between maturational timing and sedentary behaviour (in 100% and 53% of studies in boys and girls, respectively) was most commonly reported. Evidence supporting an association between maturational timing, sport participation, and active transportation were inconsistent.

Conclusions: While this review demonstrates some evidence for early maturational timing as a risk factor for disengagement from physical activity and increase in sedentary behaviours, the reviewed literature also demonstrates that this relationship is complex. Future research that tracks maturity-related variations in physical activity and sedentary behaviours over adolescence is warranted.

Keywords: adolescent; maturational timing; physical activity; sedentary behaviour; sports participation

Introduction

Physical activity contributes to the physical and mental health of children and adolescents (Cooper 2019). Specifically, children and adolescents who are regularly physically active tend to have healthier body composition (Hills et al. 2011), improved cardiometabolic (Ekelund et al. 2012), musculoskeletal (Tan et al. 2014), cognitive (Gunnell et al. 2019), and mental health outcomes (Dale et al. 2019) compared with their less active peers. Increasing physical activity and reducing sedentary behaviour (i.e., time spent sitting) among children and adolescents is a major public health goal in most countries (Heath et al. 2012), with the notion that physical activity behaviours adopted in childhood will track into adulthood (Hayes et al. 2019), and thus, translate into lifelong health.

Despite the known benefits of being active, the majority of children and adolescents globally do not achieve the minimum recommended level of physical activity (Cooper et al. 2015; Guthold et al. 2020). Adolescence appears to be the period when the most notable decline in physical activity occurs, with girls being less active than boys, on average, at each chronological age (Farooq et al. 2020). This sex difference may be partially attributed to the differences in the age of onset of puberty between boys and girls (Thompson et al. 2003; Sherar et al. 2007); however, the role of biological maturation in the disengagement from physical activity during adolescence is less well studied. The rate and timing of this age-related decline in physical activity has also been shown to vary *within* sex (Dumith et al. 2011; Kwon et al. 2015), and may be related to a number of psychosocial (e.g. perception of personal characteristics, and/or friend and parental supports), environmental (e.g., access to school and community resources) and biological (e.g., heredity, sex, body composition) factors (Cumming et al. 2012; Eime et al. 2015). Although the tracking or stability of physical activity levels across puberty seems to be improved when biological maturation is considered (Erlandson et al. 2011), the relationship between biological maturity and physical activity behaviours and other behaviours (e.g., sedentary behaviours, sports participation, active transportation) is currently not well understood (Sherar et al. 2010).

Biological maturation denotes progression to the mature (i.e., adult) state which varies in timing and tempo; where *timing* refers to the time at which a maturity-event occurs and *tempo* refers to the rate at which each maturity event is attained (Malina et al. 2004). To that end, there are several methods used to assess the maturational process (e.g., skeletal and dental age, secondary sexual characteristics) and/or events [e.g., age at menarche, age at peak height velocity (APHV)] (Baxter-Jones et al. 2005; Cameron & Bogin, 2012). The inter-individual variability in the timing and tempo of growth can lead to large maturational differences between youth of the same chronological age both between and within sex (Baxter-Jones et al. 2005). The differential timing of biological maturity between children of the same chronological age is likely a contributor to the variability of physical activity participation during adolescence given the psychosocial (e.g., confidence, leadership) and biological/physical (e.g., body size, body composition) consequences of early- or late-maturation (Cumming et al. 2012).

To the authors knowledge two reviews have been published that examine the relationship between maturational timing and physical activity, the first was published by Sherar and colleagues (Sherar et al. 2010) who identified 10 unique studies. Five years later an updated review was published (Bacil et al. 2015) identified one further study. Both reviews concluded there was little consistency in the findings (i.e., being an early or late maturer was not consistently associated with disengagement nor participation in physical activity) which the authors postulated was due in part to the heterogeneity of the assessment of both maturity indicators and physical activity. Given the fairly routine adoption of device-based (i.e., accelerometry, pedometry) measurement in studies of movement behaviours within the last decade it is anticipated that more papers will be identified since the last review that use objective measures. Further, both papers focused solely on the relationship between biological maturation and physical activity, and did not include other elements on the activity spectrum such as sedentary behaviours, sports participation, or active transportation, all of which may have their own unique relationship with maturational timing. Lastly, these previous reviews were limited in that they did not use a standardized systematic review approach. Standard approaches such as PRISMA, have shown to increase completeness, methodological quality, transparency, and reliability of reviews (Moher et al. 2015). Thus, there is a need to update and replicate the previous reviews.

Sedentary behaviour is a distinct behaviour to physical activity (Saunders et al. 2014) that may have unique associations with biological maturity. High levels of sedentary behaviour are an independent predictor of poor physical (Carson et al. 2016) and mental (Hoare et al. 2016) health in children and, although related to physical inactivity, it can also co-exist with meeting physical activity guidelines in some children. An age-related increase in sedentary behaviours, including screen time, has been observed across adolescence (Brodersen et al. 2007); however, whether biological status is a risk factor for increased sedentary behaviour, the direction (i.e., whether early or late maturers are at greater risk), and whether the association differs by gender is currently unknown. Plausible rationale for an association between maturational timing and sedentary behaviours includes the mimicking of more adult-like, sedentary behaviours among early maturing youth, a decreased desire for active play behaviours, and/or an increased appeal for increased sedentary social activities (e.g., Ingram 2000; Sallis 2000). Furthermore, participation in organised sport is a highly valuable and frequent form of physical activity in adolescents and might have its own unique association with maturity status that is diluted when looking at total physical activity. For example, early maturing children may be better suited for sports that require strength or coordination, whereas late maturing children may be better to sports that require a smaller body frame (e.g., Moore et al. 2010). Most literature that assesses the relationship between biological maturation and sport focuses on elite, competitive athletes, and is specific to talent identification and sports success (Malina et al. 2015). Fewer studies describe the role of maturational timing in the participation in recreational sports. Finally, actively commuting to school or within the community may be a means of increasing physical activity during childhood. Active transport (i.e., walking, biking, scooting, wheeling) has been shown to been positively associated with children's physical activity but not sedentary behaviour (Schoeppe et al. 2013). As a child progresses through adolescence they become independently more mobile with a wider roaming distance (Garcia-Cervantes et al. 2016); however, the evidence surrounding whether early or late maturing children are more or less likely to engage in active transportation has yet to be systematically reviewed.

Given the limited and ambiguous findings currently available, this study aimed to update and expand on the previously published reviews, by systematically reviewing (using a comprehensive and rigorous search strategy), and identifying studies that examined the relationship between maturational timing and physical activity (including sports participation and active transport) and sedentary behaviours in boys and girls.

Materials and Methods

Protocol and registration

This systematic review was registered in the International Prospective Register of Systematic Reviews (PROSPERO; Registration no. CRD42020146695; available from https://www.crd.york.ac.uk/prospero/), and conducted and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al. 2009).

Study eligibility criteria

We sought to identify any study that examined the relationship between maturational timing and physical activity, sports participation, and/or sedentary behaviour. The Population, Intervention (Exposure), Comparisons, Outcomes, and Study designs (PICOS) framework (Schardt et al. 2007) was utilized to facilitate the search process.

Population

The population of interest included apparently healthy children and adolescents with no known conditions that may influence growth, maturation, or physical activity. Studies involving elite athletes (e.g., enrolled in professional academies) were excluded.

Exposure

The exposure included studies with described biological maturity (e.g., stage of secondary sex development), maturational status (i.e., pre-pubertal, circa-pubertal, post-pubertal, and all variants) or maturational timing (early-maturing, average-maturity, late-maturing, and all variants). Studies with a measurement of actual or predicted maturity, such as skeletal age, dental age, serum or salivary sex hormones, secondary sexual characteristics (i.e., public hair development in boys or girls, genital development in boys, breast development in girls), age at menarche in girls, age at spermarche or voice changes in boys, age at peak velocity (APHV) or other growth curve parameters (e.g., age at take-off), percentage of adult stature, including all composites (e.g., pubertal development scale, PDS) were included.

Comparison (control)

No control grouping was used in this study. Instead the use of alternative maturity groupings (e.g., pre- compared with post-pubertal, early-maturing compared with late-maturing) were employed for comparison, where reported.

Outcomes

The primary outcome consisted of measured physical activity and/or sedentary behaviours, including all closely associated term variants (e.g., recreational sports participation or active transportation when reflective of physical activity, screen time, television viewing). Studies with an objective/device (e.g., accelerometer-based physical activity) and/or subjective (e.g., self-reported physical activity) measurement of physical activity or sedentary behaviour were included.

Study designs

Published and in-press (or published online ahead of print) peer-reviewed original manuscripts in English were included. Manuscripts, regardless of study design were considered applicable for analyses. Any grey literature and conference abstracts were excluded.

Information sources and search strategy

Search terms were chosen through consultation with the study's authors and subject matter experts and divided into three major concepts: 1) children and adolescents, 2) maturational timing, and 3) physical activity. We identified and searched six electronic bibliographic databases using published recommendations for database searches (Reed and Baxter 2009). The search design was adapted for each of the following databases, using a combination of keywords, and, where available, subject headings mapped to the keywords: MEDLINE with Full Text, EMBASE, PsycINFO, Cochrane Central Register of Controlled Trials, SPORTDiscus, and Web of Science Core Collection. The search was conducted by a member of the study team (SAM) and a university librarian. Search dates included from database inception to August 1, 2019. To complete the search strategy, reference list searches and forward citation searches of the two existing reviews (Sherar et al. 2010; Bacil et al. 2015) and included studies were conducted. A final follow-up search was conducted prior to submission and databases were searched using the same protocol (SAM) from August 1, 2019 to May 15, 2020. Details of the search strategies (e.g., keywords) can be found in Supplemental File 1.

Bibliographic records were extracted as RIS files from the interfaces and imported into Covidence (Covidence Systematic Review Software, Veritas Health Innovation, Melbourne, Australia), a secure internet-based software that allows reviewers to independently screen records against inclusion criteria. Two reviewers (SAM, GB) independently examined all title and abstracts. Inclusion by both reviewers was required for a study to progress to full text review. The same two reviewers independently examined all full-text articles. Consensus was needed for the article to be included in the review. Discrepancies were resolved by discussion between the reviewers, or with the larger research team (LS, SC), when required. Once the final articles were selected, a manual reference search and forward citation search of all included articles was conducted to check for missing papers (SM, GB). All included articles were approved by three members of the study team (SAM, LS, SC) prior to data extraction.

Data Extraction and Coding

Pertinent information from each article was extracted by two reviewers (SAM, KR) independently into Microsoft Excel and checked for accuracy. The data extraction table included: citation, study design, country, sample size and description (e.g., age and sex of participants), measure/indicator of maturity, measure of physical activity, key findings (i.e., relationship between maturity and physical activity), and statistical approach (including covariates used in analysis), where applicable. To assess maturational timing there is a need to have considered chronological age in the analysis. Data were coded as not significant (i.e., there was no noted association between maturation timing and the outcome), inverse [i.e., earlier/advanced maturation was associated with a decrease in the outcome (e.g., *earlier/advanced* maturers were *less* physically active)] or positive [i.e., earlier/advanced maturation was associated with an increase in the outcome (e.g., *early/advanced maturers* were *more* sedentary)]. After coding, we indicated if the study controlled for age in their analyses. This could be done by examining a narrow age range of participants (e.g., one grade in school), using a measure that adjusts for chronological age (e.g., APHV) or by controlling for chronological age in the analyses. We differentiated studies that controlled for age in the written results and associated tables.

Quality Assessment

Study quality was assessed by two reviewers (SAM, KR) independently using 10 or 12 quality criteria items for cross-sectional and longitudinal studies, respectively. The scale (Supplemental File 2) was modified from existing quality criteria lists used in reviews of observational research (Jones et al. 2013; Tanaka et al. 2014; Pearson et al. 2017). The criteria represent four dimensions of study quality: a) study population and participation, b) data collection, c) data analysis, and d) study attrition (where applicable). Criteria were assessed as ‘yes’ (=1) when the study meets the described criteria, ‘no’ (=0) when the study does not, or ‘unknown’ (=0) when the study has an incomplete or missing description which prevents a judgement to be made. Studies scored higher when data were collected using more objective measures of physical activity (criteria #3 and 4) and/or biological maturity (criteria #5 and 6). The scores were summed and converted to a percentage to indicate overall quality of the article. A paper was deemed to have high methodological quality if it scored ≥70%, moderate quality if it scored 50-69%, and low quality if it scored <50% (Jones et al. 2013). Discrepancies between reviewers were discussed until consensus was reached.

Analysis

A narrative synthesis was conducted using a previously published methodological framework (Rodgers et al. 2009). A preliminary synthesis, by study design and outcome, was produced, identifying trends within and between studies. Studies were further interpreted based on measures, as well as age and sex of participants.

Results

Description of screening results and included studies

The identification, screening, eligibility, and inclusion of studies is described in a PRISMA flow (Figure 1). The search of electronic databases yielded 13,851 records (MEDLINE with Full Text=3218, PsycINFO=2308, Cochrane Central Register of Controlled Trials=450, SPORTDiscus=1572, EMBASE=3697, and Web of Science Core Collection=2606). Duplicates (n=3695) were removed. The reference searches and forward citations searches from the two existing reviews (Sherar et al. 2010; Bacil et al. 2015) yielded 187 (100 references and 87 citations) and 47 records (31 references and 16 citations), respectively. The follow-up search prior to article submission yielded an additional 489 records (MEDLINE with Full Text=190, PsycINFO=31, Cochrane Central Register of Controlled Trials=15, SPORTDiscus=78, EMBASE=190, and Web of Science Core Collection=148). Duplicates (n=73) were removed.

[Insert Figure 1]

The three searches combined yielded 10,576 records after removing duplicates. The two reviewers agreed on 94% (n=9,941) records from the title and abstract screening and 98% (n=624) from the full text screening. After full text review, a total of 78 studies (0.7% of total) remained (56 cross-sectional; 22 longitudinal). Reasons for excluding studies during full-text review included: record was an abstract only (e.g., conference proceeding) (n=30), full text was not available or could not be found (n=2), full text was not an original research article (e.g., was a review, commentary, editorial note, etc.) (n=27); full text did not report physical activity/sedentary behaviour (n=362), full text did not report biological maturity or maturational timing/status (n=60); full text did not report the relationship between the aforementioned and physical activity/sedentary behaviour (n=78).

Study quality

Table 1 presents the methodological quality criteria and scores. The quality of the studies ranged from 30.0% to 91.7%. Of the 78 studies, 56 (74.7%) were considered 'high' quality, 17 (22.7%) 'moderate', and 2 (2.7%) 'low' quality. With regards to specific quality criteria, the majority of studies (97.3%; criteria 2) provided adequate description of the study's sample characteristics; however, most did not report an adequate description of the sampling recruitment details (34.7%; criteria 1). A description of the methods related to physical activity assessment (criteria 3 and 4) were described in detail in the majority of studies (96.0% and 85.3%, respectively). Similarly, a description of the methods related to the assessment of maturation was described adequately in most studies (92.0%; criteria 5); yet, few studies (14.6%) included an objective measure of a biological indicator (criteria 6); with majority using a measure that relied on prediction or self-assessment/report. The majority of studies provided a detailed description of the sample characteristics (90.7%; criteria 7). In studies that assessed both sexes, 84.0% separated the analysis by sex (criteria 8). More than two thirds of studies had >250 participants (69.3%; criteria 9) and used appropriate analysis and presentation of the data (specific to the analysis of the relationship between physical activity and maturation; 68.0%; criteria 10). The majority (90.9%) of the longitudinal studies (n=12) reported the duration of follow-up (criteria 12), whereas fewer reported details of participants lost to follow-up (77.3%; criteria 11).

[Insert Table 1]

Sample characteristics

The 78 articles (64 studies with unique samples) represented 242,316 (153,179 unique, 43% boys) participants from 48 different countries across six continents. The mean age (when reported (72%)) ranged from 7.6 to 16.6 years in 77 of 78 studies (one retrospective study, mean age was 27.9 years). Forty-nine studies assessed both boys and girls (63%), whereas twenty-seven studies measured only girls (35%) and only two studies (3%) measured boys only.

Description of measures

Almost half of the studies measured maturity using self-reported tools (n=36; e.g., self-reported secondary sexual characteristics (n=10) (Tanner et al. 1966b, 1966a), status quo method of recalling age at menarche or spermarche (n=10), pubertal development scale (n=18) (Petersen et al. 1988)). Several of the studies also used prediction equations (n=28), such as predicted age at peak height velocity (APHV; n=18) (e.g., Mirwald et al. 2002; Moore et al. 2015) or percentage of predicted adult height (n=10) (Khamis and Roche 1994). Fewer studies measured maturity using more objective tools (n=14) such as physician assessed secondary sexual characteristics (n=10), serum sex hormones (n=2), skeletal age (n=2) or actual APHV calculated with longitudinal data (n=2). Several studies used more than one maturity assessment (n=6). Of the studies that assessed physical activity, the majority of studies measured self-reported physical activity (n=43), whereas only 31 studies used devices to measure physical activity (i.e., accelerometers (n=26) or pedometers (n=5)). Of studies that assessed sedentary behaviours, the majority used questionnaires (n=13), compared with device-measured sedentary (or statioanry) time using accelerometers (n=6) or pedometers (n=1). An additional seven studies measured participation or drop-out from sport using questionnaires, and two studies assessed active transportation by questionnnaire (n=2) and GPS (n=1).

Maturational timing and physical activity

Tables 2 and 3 provide an overview of the studies that assess the relationship between biological maturity and device and questionnaire-assessed physical activity, respectively. A total of 74 and 20 studies were identified that explored the association between biological maturity and physical activity and sedentary behaviour, respectively. Of these studies, 61 studies (82%) and 17 studies (85%) controlled for chronological age (and thus will only be considered from this place forward). Those studies that did not control for age are identified in the tables with a symbol (†).

A total of 31 studies, representing 26,024 participants, used device measures (accelerometry =26; pedometry =5), of which 24 studies included age in their analysis (of which, 15 reported findings in boys and all 24 reported findings in girls), representing 17,087 participants. Of the 15/24 studies that assessed boys, nine studies (60%) found an inverse relationship between biological maturity and physical activity [i.e., early maturing (more mature) boys with were less active] and six (30%) found no significant associations or differences between maturity groups. Of the 24/24 studies that assessed girls, 12 (50%) found an inverse relationship between biological maturity and physical activity [i.e., early maturing (more mature) girls were less active] and 12 (50%) found no significant associations or differences between maturity groups. In three studies, the results varied by physical activity outcome.

A total of 43 studies, representing 203,866 participants, used questionnaires to assess physical activity, of which 37 studies included age in their analysis, representing 200,244 participants. In the 37 studies, 19 reported findings in boys and all 37 reported findings in girls), Of the 19/37 studies that assessed boys, 10 studies (53%) found an inverse relationship between biological maturity and physical activity [i.e., early maturing (more mature) boys were less active], seven studies (37%) found no significant associations or differences, and 2 studies (11%) found a positive relationship [i.e., early maturing (more mature) boys were more active]. Of the 37/37 studies that assessed girls, 19 studies (51%) found an inverse relationship between biological maturity and physical activity [i.e., early maturing (more mature) girls were less active], 16 studies (43%) found no significant associations or differences, and one study (3%) found a positive relationship between biological maturity and physical activity [i.e., early maturing (more mature) girls were more active]. In six studies, the results varied by outcome (e.g., Benefice et al. 2000 found an inverse relationship between maturational timing and physical activity in evening physical activity but not day-time physical activity; Garnier et al. 2001 found an inverse relationship between maturational timing and physical activity in city dwelling girls but not girls living in rural environments, etc.).

[Insert Table 2]

[Insert Table 3]

Maturational timing and sedentary behaviours

Table 4 provides an overview of the studies that assessed the relationship between maturational timing and device and questionnaire-measured sedentary time. A total of 20 studies (7 device-measured, 13 questionnaire measured), representing 98,521 participants assessed this relationship, of which 16 studies included age in their analysis, representing 95,379 participants.

Given there were fewer studies that assessed the relationship between biological maturity and sedentary behaviours we collapsed the results for device and questionnaire-measured results. Of the 11/20 studies that assessed boys, all 11 studies (100%) found a positive association between maturational timing and sedentary behaviours [i.e., early maturing (more mature) boys were more sedentary], though two studies (18%) found that results varied by behaviour (e.g., positive association with television viewing, no significant associations with video games). Whereas of the 15/20 studies that assessed girls, eight studies (53%) found a positive association between maturational timing and sedentary behaviours [i.e., early maturing (more mature) girls were more sedentary] and seven studies (47%) found no significant associations or differences between maturity groups. In five studies, the results varied by outcome. Briefly, studies that used questionnaire-based measurement of physical activity were more likely to report a positive relationship between biological maturation and sedentary behaviours (8/13 and 7/13 studies in boys and girls, respectively reported a positive association) compared with device-based measures (3/7 studies in both sexes reported a positive association) [i.e., early maturing (more mature) children were more sedentary].

[Insert Table 4]

Maturational timing and sports participation and active transportation

Table 5 provide an overview of the studies that assess the relationship between maturational timing and sports participation or active transportation. A total of seven studies, representing 5,107 participants, assessed the relationship between maturational timing and sports participation (e.g., attendance in recreation sports), of which seven studies included age in their analysis, representing 2,964 participants. Of the five studies that assessed boys, three studies (60%) noted an inverse relationship between biology maturity and sports participation [i.e., early maturing (more mature) boys had lower recreational sports participation] and two studies (40%) noted no significant associations or differences. In the four studies that assessed girls, two studies (50%) noted an inverse relationship between biology maturity and sports participation [i.e., early maturing (more mature) girls had lower recreational sports participation] and two studies (50%) noted no significant associations or differences. A total of two studies, representing 992 participants, assessed the relationship between maturational timing and active transportation (e.g., walking, biking, scooting). Both studies included age in their analyses and measured both boys and girls; however, neither study found a relationship or association between biological maturation and active transportation.

[Insert Table 5]

Discussion

The aim of this systematic review was to summarize the literature that described the relationship between maturational timing and physical activity and sedentary behaviour in adolescents. The current review found no overarching agreement in the literature for associations between biological maturity and physical activity among adolescents, which is in line with the previous review published on this topic, despite increasing the amount of included papers sevenfold (Sherar et al. 2010; Bacil et al. 2015). However, there was modest evidence for early maturity being associated with less activity and more sedentary behaviours. Specifically, after excluding studies that did not control for age in their analysis, we found that half or greater (60% in boys, 50% in girls) of device-measured physical activity studies found that early/advanced maturation was associated with lower physical activity. Similar results were observed in studies that used questionnaire-measured physical activity. In studies that measured sedentary behaviours, all studies in boys and more than half of studies in girls (100% and 53%, respectively) found a positive association between biological maturity and sedentary behaviours (i.e., early/advanced maturation was associated with higher levels of sedentary behaviours) although the number of identified studies focusing on sedentary behaviour were much less.

Conversely, the findings were inconsistent and variable for the studies that assessed the relationship between biological maturation and recreational sports participation. Further, none of the small number of studies that measured active transportation found a relationship with biological maturity. Previous authors (Baxter-Jones 1995; Cumming et al. 2012) have postulated that early maturity may be supportive of physical activity engagement (specially sport) in boys and a barrier to engagement in girls. The main rationale for this supposition, is that pubertal changes in boys leads to increased absolute and relative muscle mass, anaerobic power, and strength gains (Brown et al. 2017) which would be considered conducive to sporting performance success. Whereas pubertal changes in girls leads to increased absolute and relative fat mass, widening of the hips, and breast development (Barbour-Tuck et al.

2018) which may be considered a barrier to sport performance and participation. However, the literature that supports this conjecture, tends to come from studies of more select or elite groups of young athletes (Malina et al. 2015). To the authors knowledge this is the first comprehensive systematic review of literature that examined daily and recreational physical activity and participation in sport (i.e., not at an elite level).

The inconsistency in the findings may be due, in part, to varied indicators and/or measures of biological maturity and outcome measures of physical activity and sedentary behaviour. A number of indicators and protocols were used to assess biological maturity across the studies in the current review, which differ in their degree of accuracy. Indicators included the pubertal development scale (PDS), recalled age at menarche, hormonal assays, APHV (predicted and directly estimated), and secondary sex characteristics. A full appraisal of the methods used to assess maturity is beyond the scope of this discussion and a more complete discussion can be found elsewhere (e.g., Baxter-Jones et al. 2005; Cameron & Bogin, 2012). However, it should be noted that only three studies used the 'gold standard' measures (i.e., skeletal age assessment via hand-wrist radiographs or attained APHV (i.e., using serial measures of height via longitudinal assessment). Certainly, the cost, time, and/or ethical issues in using these methods have enhanced the popularity of a number of prediction (e.g., using anthropometry-based equations) and/or self-reported measures (e.g., secondary sexual characteristics) of biological maturity (Baxter-Jones et al. 2005). However, these measures will have varied accuracy which will depend largely on the testing protocol and age of the participants. For example, recalled age at menarche has error associated with memory and some studies show limited agreement between children reported and clinician reported secondary sex staging (Desmangles et al. 2006). Further, prediction equations may be less accurate the further the prediction is made from the actual time of maturity indicator (Mirwald et al. 2002; Moore et al. 2015).

Accuracy aside, the indicators used across the studies focuses fairly evenly on sexual maturity (PDS, self-reported secondary sex staging, age at menarche or spermarche) and somatic maturity (e.g. predicted APHV, and predicted percentage of adult height). Although these indicators are related (Beunen et al. 2006) (i.e., if the timing is early in one, it is likely to be early in another) they may hold very different meanings for an individual. For example, unlike the other gradual changes during adolescence, menarche is sudden and noticeable, and it provides a rather dramatic demarcation between girlhood and womanhood (Chang et al. 2010) and thus this event in itself might lead to a girl to disengage from physical activity, especially from activities that could be perceived as childish. However, this is challenging to ascertain and would require longitudinal study that tracks activity in girls over time to see whether the age at menarche event leads to a reduction in activity.

It could be argued that some of the inconsistency by study finding could also be due to the heterogeneity of age range included in the studies. Although the majority of studies controlled for age in their analysis, some studies did not. Studies with a narrow age range do not necessarily need to control for chronological age, however, other studies with wider chronological ages should include age as a covariate in their analysis if they wish to comment on the influence of maturity timing. For example, the studies that did not control for age in their analysis most commonly reported unadjusted bivariate correlations, making it impossible to discern whether this association was due to increase in chronological or biological age. Though in our case, when we removed the 13 studies that did not control for age in their analysis, the proportion of studies reporting inverse, positive, or no associations did not change. Similarly, when we only included studies with 'high' quality, the proportion of studies reporting inverse, positive, or no associations did not change. We strongly urge future authors that aim to assess the relationship between biological maturity and physical activity or sedentary behaviours to consider limiting age range, using maturity categories or z-scores, or control for age in their analyses.

The associations between maturation, physical activity, and sedentary behaviours may also vary relative to the nature of the sample studied. In accordance with the early maturation hypothesis, those studies reporting the strongest associations among maturation, physical activity, and sedentary behaviour in girls have focussed upon individual at the extremes of the maturity continuum (i.e., the most vs least mature girls within each school year). It is possible that being on-time or slightly advanced and/or delayed in maturation has limited bearing upon one's physical activity or sedentary behaviour. Rather it is the adolescents at the extreme ends of the maturity continuum that are most likely to vary in their physical activity or sedentary behaviour. In support of this contention girls at the extreme ends of the maturity continuum also demonstrate markedly greater variation in physical self-concept, with the most mature girls reporting lower perceptions of physical attractiveness, physical conditioning, sports competence, and physical self-worth compared with later maturing peers (Cumming et al. 2011). Future research should seek to further examine the extent to maturity associated variance in physical activity and other health related behaviours and constructs varies relative to maturity continuum in boys and girls.

The number of studies that do not show an association could also be because device-measured physical activity measures any minute of activity and thus all types of activity including sporadic, lifestyle embedded activity. If the disengagement from activity that is associated with biological maturity is a decision, an option to drop out, then this may be identified via self-reported measures of physical activity as the questionnaires tend to collect information on purposeful bouts of more organised activity that can be recalled. Devices, such as accelerometers or pedometers, on the other hand collect total physical activity (including very short bouts such as 15 or 30 seconds) of moderate to vigorous physical activity (MVPA). In children and adolescents, we know that much of the activity is derived from incidental or lifestyle embedded physical activity which could be considered more compulsory (such as walking to school, chores/work) and this type of activity is included within the accelerometer/pedometer derived physical activity variables. It is possible decisions to disengage from physical activity might be more apparent in self-reported measures than device measures because of the incidental, compulsory activity that the accelerometers/pedometers are assessing. However, it did appear that, at least in boys, there were slightly more studies that showed an inverse association between biological maturity and physical activity when using devices compared with questionnaires. Lastly, a known disadvantage of questionnaires surrounds bias due to social desirability. It is possible that early-maturing girls, in particular, may be more prone to this bias because of a tendency for greater fat mass, lower body satisfaction, and lower self-esteem (Susman and Rogol 2004).

Arguably, a true understanding of the relationship between maturation and physical activity resides in the simultaneous and interactive effects of biological, psychosocial, behavioural, and cultural factors. The processes of growth and maturation do not exist in social and/or cultural vacuum and the physical, morphological, and functional changes that company these processes have important stimulus value for both the individual and society. That is, how an individual perceives the changes associated with growth and maturation and the reactions and evaluations of others is as, if not more, important than change itself. For example, a girl who matures early but perceives maturation as a natural and positive consequence of progress towards adulthood and not as a barrier towards activity may less likely to become inactive during this stage of their development. Similarly, an early maturing girl growing up in a society or culture where physical activity is value and they feel accepted and supported by her peers, family, and/or teachers may be just as likely to remain active through puberty as their late maturing peers. To better understand the complex and dynamic nature of these associations it is imperative that researcher adopt a biocultural perspective and more holistic approach to the study of adolescent growth and development. As such, a number of included studies presented potential mediation models, describing the direct and indirect relationship between biological maturity and physical activity (Davison et al. 2007; Cumming et al. 2011; Hunter Smart et al. 2012; Jackson et al. 2013; Pindus et al. 2014; Lee, An, et al. 2016; Lee et al. 2017; Werneck, Silva, et al. 2018; Steppan et al. 2019; Voskuil et al. 2019), sedentary behaviours (Lee, An, et al. 2016; Lee et al. 2017), and sports participation (Werneck, da Silva, et al. 2018). These models consider the direct and indirect mediated effects of biological maturity on movement behaviours. In future, those studying the effects of maturation on physical activity and sedentary behaviour in youth would benefit from framing their research within contemporary theories of adolescent development that recognise the potential for these direct and indirect effects of maturation upon adolescent behaviour (Cumming et al. 2012). The context amplification hypothesis (Kretschmer et al. 2014), for example, assumes that the effects of biological maturation upon health related and risk-taking behaviours will be greater in social contexts that provide limited supervision and support for the child.

The relationship between sedentary behaviour and biological maturity has been less well studied. This review identified 20 studies that assess this relationship. It is now accepted that sedentary behaviour and physical inactivity are distinct behaviours and a child can be both active and sedentary (Saunders et al. 2014), and as a child ages they become more sedentary (van Ekris et al. 2020). However, the mechanism by which biological maturity may impact sedentary behaviour is not well understood. We know that biological maturity is associated with enhance weight (and in particular fatness in girls) (Davison et al. 2003; Kaplowitz 2008). Fat mass and weight status are correlates of sedentary behaviour, including screen time, among adolescents (Salmon 2011). Likewise, scant literature does suggest that early biological maturity may be a risk factor for poor mental health (Galvao et al. 2014). Furthermore, higher amounts of sedentary behaviour has a small but consistent negative effect on mental health including higher levels of depressive symptoms (Maras et al. 2015) and lower self-esteem (Russ et al. 2009). It is likely that a combination of social, psychological, and physical changes that occur with biological maturity may underlier any association with sedentary behaviour (Lee, An, et al. 2016; Lee et al. 2017) and warrants further research.

Future research

There is a need to have a better theoretical understanding of how timing of biological maturity may influence physical activity and sedentary behaviour through a biocultural lens. The chances of reaching a consensus in the literature would be enhanced if there were more consistency in the measures used to assess biological maturity with an aim to use skeletal age assessment and/or attained APHV. Lastly, it is still unclear as to how biological maturity influences different physical activities (i.e., total, light, moderate, vigorous) and it would be worthwhile to explore the studies that assess physical activity using devices more comprehensively to better understand these intricacies.

Strengths and limitations

This review adopted rigorous systematic procedures and reported findings according to standardized PRISMA guidelines. We utilized broad electronic and manual search criteria and two reviewers independently screened a large number of studies (~15,000) for eligibility. We were limited by the heterogeneity of the included study's methods, which in turn meant that a meta-analysis was not possible. We also acknowledge that our searches were confined to peer reviewed journals and articles written in English. Finally, given the heterogeneity of the included studies, we opted to adopt and modify a quality tool. We used arbitrary cut-offs to define high, moderate, and low quality. However, we also reported the numerical value for each included study.

Conclusion

This review demonstrates evidence that early biological maturation may be a risk factor for disengagement from physical activity and an increase in sedentary behaviours in boys and girls. Future research that tracks maturity-related variations in movement behaviours (i.e., physical activity and sedentary behaviours) over the adolescent period is warranted.

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Declaration of interest statement

Nothing to declare.

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Figure Caption.

Figure 1. Flow diagram for the identification, screening, eligibility, and inclusion of studies that assessed the relationship between maturational timing and physical activity.

Table 1. Summary of quality assessment results and overall quality score for all included studies.

	A		B				C					D				
First Author and Year of Study	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	Total for Cross-sectional Studies (/10)	**11**	**12**	Total for Longitudinal Studies (/12)	Overall Percent	Overall Quality Rating
Adoor 2019	0	1	1	1	0	0	1	1	0	1	6				60	Mod
Alfano 2002	1	1	1	1	0	0	1	1	1	1	8				80	High
Allen 2015	0	1	1	0	1	0	1	0	1	1	6	1	0	7	58	Mod
Altıntaş 2014	0	1	1	1	1	0	1	1	1	1	8				80	High
Ayele 2013	1	1	1	0	1	0	1	1	1	1	8				80	High
Baker 2007	0	1	1	1	1	1	1	1	0	1	8	0	1	9	75	High
Barkai 2007	1	1	1	1	1	0	1	1	1	0	8				80	High
Beghin 2019	0	1	1	1	1	1	1	1	1	0	8				80	High
Benefice 2001	0	1	1	1	1	0	1	1	1	0	7	1	1	9	75	High
Benítez-Porres 2016	1	1	1	1	1	0	1	1	0	1	8	1	1	10	83	High
Britton 2004	1	1	1	0	1	1	1	1	0	0	7				70	High
Brodersen 2005	1	1	1	0	1	0	1	1	1	1	8				80	High
Butte 2014	1	1	1	1	1	0	1	1	1	1	9	1	1	11	92	High
Cumming 2008	0	1	1	1	1	0	1	1	0	1	7				70	High
Cumming 2009	0	1	1	1	1	0	1	1	0	1	7				70	High
Cumming 2011	0	1	1	1	1	0	1	1	1	1	8				80	High
Cumming 2012	0	1	1	1	1	0	1	1	0	1	7				70	High
Cumming 2014	1	1	1	1	1	0	1	1	1	1	9	1	1	11	92	High
Davison 2007	1	1	1	1	1	1	1	1	0	1	9	1	1	11	92	High
Drenowatz 2010	0	1	1	1	1	0	1	1	1	1	8				80	High
Drenowatz 2013	0	1	1	1	1	0	1	1	1	1	8				80	High
Duncan 2007	0	1	1	1	1	0	0	0	1	0	5				50	Mod
Fawkner 2014	0	1	1	1	1	0	1	1	0	0	6	1	1	8	67	Mod
Finne 2011	0	1	0	0	1	0	1	1	1	0	5				50	Mod
Gammon 2017	0	1	1	1	1	0	1	1	1	0	7				70	High
Garcia 2018	0	1	1	1	1	1	1	1	1	1	9				90	High
Garnham-Lee 2017	0	1	1	1	1	0	1	1	1	1	8				80	High
Garnier 2001	0	1	1	1	1	1	1	1	1	0	8	0	1	9	75	High
Gebremariam 2012	1	1	1	1	1	0	1	1	1	1	9	1	1	11	92	High

Gilmer 2003	0	1	1	1	1	0	1	0	0	1	6				60	Mod
Gomes 2017	0	1	1	1	1	0	0	0	1	0	5				50	Mod
Guinhouya 2013	0	1	1	1	1	0	1	1	1	1	8				80	High
Hearst 2012	1	1	1	1	1	0	1	1	1	0	8	0	0	8	67	Mod
Herman 2015	1	1	1	1	1	1	1	0	1	0	8				80	High
Hunter Smart 2012	0	1	1	1	1	0	1	1	0	1	7				70	High
Jackson 2013	0	1	1	1	1	0	1	1	0	1	7				70	High
Kemper 1997	0	0	1	0	1	1	1	0	1	0	5	1	1	7	58	Mod
Knowles 2009	0	1	1	1	1	0	1	1	0	1	7	1	1	9	75	High
Kristensen 2008	1	1	1	1	1	0	1	1	1	1	9	1	1	11	92	High
Labbrozzi 2013	0	1	1	1	1	0	1	1	0	1	7				70	High
Lätt 2015	0	1	1	1	1	0	1	1	1	1	8				80	High
Lee 2016a	1	1	1	1	1	0	1	1	1	1	9				90	High
Lee 2016b	1	1	1	1	1	0	1	1	1	0	8				80	High
Lee 2017	0	1	1	1	1	0	1	1	1	1	8				80	High
Maia 2010	0	1	1	1	1	1	1	1	1	0	8	0	1	9	75	High
Marques 2016	1	1	1	1	1	0	1	1	1	1	9				90	High
Metcalf 2015	0	1	1	1	1	0	1	1	1	1	8	1	1	10	83	High
Micklesfield 2014	1	1	1	1	1	0	1	1	1	0	8				80	High
Moghadaszadeh 2017	0	1	1	1	1	0	1	1	0	1	7	0	1	8	67	Mod
Murdey 2004	0	1	0	0	0	0	0	1	0	1	3				30	Low
Murdey 2005	0	1	0	0	0	0	0	1	0	1	3	1	1	5	42	Low
Niven 2007	0	1	1	1	1	0	1	1	0	1	7				70	High
Page 2010	0	1	1	1	0	0	1	0	1	1	6				60	Mod
Pate 2019	0	1	1	1	1	0	1	0	1	0	6	1	1	8	67	Mod
Pereira 2015	1	1	1	1	1	0	1	1	1	1	9				90	High
Pindus 2014	0	1	1	1	1	0	1	1	1	1	8				80	High
Riddoch 2004	1	1	1	1	0	0	1	0	1	0	6				60	Mod
Rodrigues 2010	0	1	1	1	1	0	1	1	1	1	8				80	High
Romon 2004	1	1	1	1	1	1	1	0	1	0	8				80	High
Sherar 2007	0	1	1	1	1	0	1	1	1	0	7				70	High
Sherar 2009	0	1	1	1	1	0	1	1	0	0	6				60	Mod
Silva 2019	1	1	0	1	0	0	1	1	1	1	8				80	High
Simon 2003	1	1	1	0	1	0	1	1	1	1	8				80	High
Solomon-Brakus 2020	0	1	1	1	1	1	0	0	0	1	6				60	Mod

Steppan 2019	0	1	0	0	0	0	1	0	1	1	4				40	Low
Thompson 2003	0	1	1	1	1	1	1	1	0	1	8	1	1	10	83	High
vanJaarsveld 2007	1	1	1	0	1	0	1	1	1	1	8	1	1	10	83	High
Vermeesch 2015	0	1	1	1	1	0	1	1	1	0	7				70	High
Visagurskienė 2012	0	1	1	1	1	0	0	1	0	1	6				60	Mod
Voskuil 2019	0	1	1	1	1	0	1	1	1	1	8				80	High
Werneck 2018a	1	1	1	1	1	0	0	1	1	1	8				80	High
Werneck 2018b	1	1	1	1	1	0	0	1	1	1	8				80	High
Werneck 2019	1	1	1	1	1	0	1	0	1	1	8				80	High
Wichstrøm 2013	0	0	1	1	1	0	1	0	1	1	6	1	1	8	67	Mod
Wickel 2007	1	1	1	1	1	0	1	1	0	1	8				80	High
Wickel 2009	0	1	1	1	1	0	1	1	0	1	7				70	High
Xing 2017	0	1	1	0	1	0	1	1	1	0	6				60	Mod
Zitouni 2012	0	1	1	1	1	0	1	1	1	0	7				70	High

*Criteria are described in Supplemental File 2. Briefly: 1=Adequate description of the sampling frame and recruitment methods; 2=Adequate description of the sample's key characteristics; 3=Adequate description of methods of data collection for physical activity; 4=Adequate measurement of physical activity; 5=Adequate description of methods of data collection for maturity; 6=Adequate measurement of maturity; 7=Adequate description of the analyzed sample; 8=Appropriate sex-specific analysis, considering age; 9=Adequate sample; 10=Appropriate statistics; 11=Adequate detail re. follow-up; 12=Adequate details re. follow-up timeline. A score of 1 is given if criteria (in Supplemental File 2) is met and a score of 0 is given if the criteria is not met.

Table 2. Summary of studies that assess the relationship between maturity and device-measured physical activity.

First Author and Year	Sample Size (Boys, Girls)	Mean Age (Range)	Maturity Assessment	Physical Activity Assessment	Summary of Results by Sex		Quality Score
Baker 2007	143 (0, 143)	11.3 y (11.0-13.0 y)	Serum estradiol Breast development P Pubertal development scale	Accelerometry	Boys n/a	Girls inverse	High
Beghin 2019†	1842 (916, 926)	16.6 y (12.5-17.4 y)	Genital development P Breast development P Pubic hair development P	Accelerometry	Boys inverse	Girls n/s	High
Benefice 2001	40 (0, 40)	13.3 y (NS)	Age at menarche Breast development S	Accelerometry	Boys n/a	Girls n/s (day) inverse (night)	High
Butte 2014†	282 (133, 149)	NS (8.0-10.0 y)	Pubertal development scale	Accelerometry	Boys and Girls n/s		High
Cumming 2014	1351 (671, 680)	NS (11.0-13.0 y)	Predicted % adult height	Accelerometry	Boys inverse	Girls inverse	High
Davison 2007	178 (0, 178)	11.3 y (11.0-12.0 y)	Serum estradiol Breast development P Pubertal development scale	Accelerometry	Boys n/a	Girls n/s	High
Drenowatz 2010	268 (0, 268)	10.3 y (9.5-11.5 y)	Predicted APHV	Pedometry	Boys n/a	Girls inverse	High
Duncan 2007	371 (185, 186)	12.1 y (12.0-17.0 y)	Pubertal development scale	Pedometry	Boys inverse	Girls n/s	High
Gammon 2017	1011 (0, 1011)	12.2 y (NS)	Pubertal development scale	Accelerometry	Boys n/a	Girls inverse	High
Garnier 2001	40 (0, 40)	14.4 y (13.4-15.3 y)	Age at menarche Breast development S	Accelerometry	Boys n/a	Girls inverse (city) positive (rural)	High

Gomes 2017†	7023 (3240, 3783)	NS (9.0-11.0 y)	Predicted APHV	Accelerometry	Boys inverse	Girls inverse	Moderate
Guinhouya 2013	253 (139, 114)	9.9 y (NS)	Predicted APHV	Accelerometry	Boys n/s (TPA) inverse (MVPA)	Girls inverse (TPA) n/s (MVPA)	High
Hearst 2012	578 (287, 291)	14.6 y (10.0-16.0 y)	Pubertal development scale	Accelerometry	Boys n/s	Girls n/s	Moderate
Kristensen 2008	1330 (592, 738)	NS (8.0-16.0 y)	Breast development ^{S} Pubic hair development ^{S}	Accelerometry	Boys n/s	Girls n/s	High
Lätt 2015	314 (314, 0)	12.0 y (10-14.0 y)	Predicted APHV	Accelerometry	Boys inverse	Girls n/a	High
Lee 2016a	236 (0, 236)	13.6 y (11.0-15.0 y)	Pubertal development scale	Pedometry	Boys n/a	Girls inverse	High
Metcalf 2015	347 (174, 173)	NS (5.0-15.0 y)	Pubic hair development ^{S} Actual APHV	Accelerometry	Boys n/s	Girls inverse	High
Moghadaszadeh 2017†	33 (15, 18)	9.8 y (9.0-19.0 y)	Predicted APHV	Accelerometry	Boys inverse	Girls inverse	Moderate
Pate 2019	652 (297, 355)	10.6 y (10.0-12.0 y)	Predicted APHV	Accelerometry	Boys and Girls inverse		Moderate
Pereira 2015	686 (305, 381)	10.5 y (10.0-12.0 y)	Predicted APHV	Accelerometry	Boys and Girls n/s		High
Riddoch 2007	5595 (2662, 2933)	11.8 y (11.6-11.9 y)	Breast development ^{S} Pubic hair development ^{S}	Accelerometry	Boys inverse	Girls inverse	Moderate
Rodrigues 2010	302 (135, 167)	14.2 y (13.0-16.0 y)	Predicted % adult height	Accelerometry	Boys inverse	Girls n/s	High

Romon 2004†	510 (257, 253)	NS (8.0-18.0 y)	Pubic hair development [P]	Pedometry	Boys inverse (ambul.) n/s (LTPA)	Girls n/s	High
Sherar 2007	401 (194, 207)	NS (8.0-13.9 y)	Predicted APHV	Accelerometry	Boys inverse	Girls inverse	High
Sherar 2009	221 (0, 221)	NS (8.0-16.0 y)	Age at menarche Predicted APHV	Accelerometry	Boys n/a	Girls n/s	Moderate
Solomon-Brakus 2020†	438 (241, 197)	11.6 y (9.0-13.0 y)	Pubic hair development [P]	Accelerometry	Boys and Girls inverse		Moderate
Vermeesch 2015†	509 (0, 509)	NS (10.0-14.0 y)	Pubertal development scale	Accelerometry	Boys n/a	Girls inverse	High
Voskuil 2019	517 (0, 517)	11.8 y (9.6-14.9 y)	Pubertal development scale	Accelerometry	Boys n/a	Girls n/s	High
Wickel 2007	139 (65, 74)	14.1 y (13.0-13.9 y)	Predicted APHV	Pedometry	Boys n/s	Girls n/s	High
Wickel 2009	161 (76, 85)	12.1 y (9.0-14.0 y)	Predicted APHV	Accelerometry	Boys inverse	Girls n/s	High
Zitouni 2012	253 (139, 114)	9.9 y (NS)	Predicted APHV	Accelerometry	Boys n/s (differed by cut-point)	Girls n/s	High

n/a = not applicable; n/s = not significant; † = did not control for age in analysis; P = physician or nurse assessed, [S] = self-assessed; APHV = age at peak height velocity; TPA = total physical activity; MVPA = moderate to vigorous physical activity; ambul = ambulatory physical activity; LTPA = leisure time physical activity.

Table 3. Summary of studies that assess the relationship between maturity and questionnaire-measured physical activity.

First Author and Year	Sample Size (Boys, Girls)	Mean Age (Range)	Maturity Assessment	Physical Activity Assessment	Summary of Results by Sex		Quality Score
Adoor 2019	100 (0, 100)	13.6 y (12.0-15.0 y)	Age at menarche	Questionnaire	Boys n/a	Girls n/s	Moderate
Alfano 2002	486 (0, 486)	27.9 y (18.0-39.0 y)	Age at menarche [R]	Questionnaire	Boys n/a	Girls inverse	High
Altıntaş 2014†	1012 (526, 486)	14.9 y (11.0-18.0 y)	Facial hair development Age at menarche Breast development [S]	Questionnaire	Boys n/s	Girls n/s	High
Ayele 2013	734 (0, 734)	NS (10.0-19.0 y)	Age at menarche	Questionnaire	Boys n/a	Girls inverse	High
Barkai 2007	99 (0, 99)	15.5 y (13.0-18.0 y)	Age at menarche	Questionnaire	Boys n/a	Girls n/s	High
Benítez-Porres 2016	80 (38, 42)	14.6 y (NS)	Predicted % adult height	Questionnaire	Boys and Girls n/s		High
Britton 2004	186 (0, 186)	9.0 y (NS)	Breast development [P] Pubic hair development [P]	Questionnaire	Boys n/a	Girls n/s	High
Brodersen 2005	4320 (2578, 1742)	11.8 y (NS)	Pubertal development scale	Questionnaire	Boys and Girls n/s		High
Cumming 2008	186 (103, 83)	14.0 y (13.6-14.7 y)	Predicted % adult height	Questionnaire	Boys inverse	Girls n/s	High
Cumming 2009	186 (103, 83)	14.0 y (13.6-14.7 y)	Predicted % adult height	Questionnaire	Boys inverse	Girls inverse (intense) n/s (LTPA)	High

Cumming 2011	407 (0, 407)	13.2 y (11.0-15.0 y)	Predicted % adult height	Questionnaire	Boys n/a | Girls inverse	High
Cumming 2012	222 (0, 222)	12.7 y (10.0-14.0 y)	Predicted % adult height	Questionnaire	Boys n/a | Girls inverse (differed by age)	High
Davison 2007	178 (0, 178)	11.3 y (11.0-12.0 y)	Serum estradiol Breast development [P] Pubertal development scale	Questionnaire	Boys n/a | Girls inverse (breast stage only)	High
Drenowatz 2013	1118 (592-526)	7.6 y (6.3-8.9 y)	Predicted % adult height	Questionnaire	Boys n/s | Girls n/s	High
Duncan 2007	371 (185, 186)	12.1 y (12.0-17.0 y)	Pubertal development scale	Questionnaire	Boys inverse | Girls n/s	High
Fawkner 2014	208 (0, 208)	11.8 y (NS)	Pubertal development scale	Questionnaire	Boys n/a | Girls inverse	Moderate
Finne 2011	6818 (3318, 3495)	14.6 y (11.0-17.0 y)	Voice development Age at menarche Pubic hair development [S]	Questionnaire	Boys inverse | Girls inverse	Moderate
Garcia 2018	750 (394, 356)	13.8 y (11.0-17.0 y)	Predicted APHV Skeletal age	Questionnaire	Boys inverse | Girls inverse	High
Gebremariam 2012	885 (466, 419)	11.2 y (NS)	Pubertal development scale	Questionnaire	Boys n/s | Girls n/s	High
Gilmer 2003†	113 (60, 107)	12.1 y (11.0-14.0 y)	Pubertal development scale	Questionnaire	Boys and Girls n/s	Moderate
Hunter Smart 2012	222 (0, 222)	12.7 y (10.0-14.0 y)	Predicted % adult height	Questionnaire	Boys n/a | Girls inverse	High
Jackson 2013	244 (0, 244)	12.8 y (11.0-14.0 y)	Predicted % adult height	Questionnaire	Boys n/a | Girls inverse	High

Kemper 1997	200 (93, 107)	NS (12.0-22.0 y)	Skeletal age	Interview	<u>Boys</u> inverse	<u>Girls</u> inverse	Moderate
Knowles 2009	105 (0, 105)	12.8 y (NS)	Pubertal development scale	Questionnaire	<u>Boys</u> n/a	<u>Girls</u> n/s	High
Labbrozzi 2013	134 (0, 134)	12.6 y (11.0-13.0 y)	Breast development [P] Pubic hair development [P]	Questionnaire	<u>Boys</u> n/a	<u>Girls</u> n/s	High
Lee 2016a	236 (0, 236)	13.6 y (11.0-15.0 y)	Pubertal development scale	Questionnaire	<u>Boys</u> n/a	<u>Girls</u> inverse	High
Lee 2016b	74186 (38221, 35965)	14.9 y (13.0-18.0 y)	Age at menarche Age at spermarche	Questionnaire	<u>Boys</u> positive	<u>Girls</u> mixed results†	High
Lee 2017	74186 (38221, 35965)	14.9 y (13.0-18.0 y)	Age at menarche Age at spermarche	Questionnaire	<u>Boys and Girls</u> n/s		High
Marques 2016	1324 (0, 1324)	NS (10.0-13.0 y)	Age at menarche	Questionnaire	<u>Boys</u> n/a	<u>Girls</u> inverse	High
Micklesfield 2015	381 (189, 192)	NS (11.0-15.0 y)	Breast development [S] Genital development [S]	Questionnaire	<u>Boys</u> n/s	<u>Girls</u> n/s	High
Niven 2007	208 (0, 208)	11.8 y (NS)	Pubertal development scale	Questionnaire	<u>Boys</u> n/a	<u>Girls</u> n/s	High
Pindus 2014	349 (0, 349)	13.2 y (11.3-14.5 y)	Predicted % adult height	Questionnaire	<u>Boys and Girls</u> inverse		High
Silva 2019	803 (402, 401)	12.9 y (10.0-17.0 y)	Predicted APHV	Questionnaire	<u>Boys and Girls</u> inverse		High
Simon 2003	4320 (2578, 1742)	11.8 y (NS)	Pubertal development scale	Questionnaire	<u>Boys</u> inverse (weekend) n/s (other)	<u>Girls</u> n/s	High

Steppan 2019	21094 (0, 21094)	NS (9.0-13.0 y)	Age at menarche	Questionnaire	Boys n/a	Girls inverse	Low
Thompson 2003†	138 (70, 68)	NS (9.0-18.0 y)	Actual APHV	Questionnaire	Boys inverse	Girls inverse	High
vanJaarsveld 2007	5229 (2982, 2247)	11.8 y (NS)	Pubertal development scale	Questionnaire	Boys positive	Girls positive (differed by age)	High
Visagurskienė 2012†	236 (115, 121)	NS (14.0-16.0 y)	Pubic hair development [S]	Questionnaire	Boys inverse	Girls n/s	Moderate
Werneck 2018a†	1152 (512, 640)	13.0 y (10.0-17.0 y)	Predicted APHV	Questionnaire	Boys n/s	Girls n/s	High
Werneck 2018b†	991 (412, 579)	13.4 y (10.0-17.0 y)	Predicted APHV	Questionnaire	Boys n/s	Girls n/s	High
Werneck 2019	1186 (525, 661)	13.4 y (10.0-17.0 y)	Predicted APHV	Questionnaire	Boys and Girls inverse		High
Wichstrøm 2013	3251 (NS)	NS (12.0-19.0 y)	Pubertal development scale	Questionnaire	Boys and Girls n/s		Moderate
Xing 2017	1530 (0, 1530)	13.7 y (NS)	Age at menarche	Questionnaire	Boys n/a	Girls inverse	Moderate

n/a = not applicable; n/s = not significant; † = did not control for age in analysis; [R] = retrospective; [P] = physician or nurse assessed; [S] = self-assessed; APHV = age at peak height velocity; † = early and late maturing girls had greater PA compared with average maturing girls.

Table 4. Summary of studies that assess the relationship between maturity and device- and questionnaire-measured sedentary behaviours.

First Author and Year	Sample Size (Boys, Girls)	Mean Age (Range)	Maturity Assessment	Sedentary Behaviour Assessment	Summary of Results by Sex		Quality Score
Device-Measured							
Butte 2014†	282 (133, 149)	NS (8.0-10.0 y)	Pubertal development scale	Accelerometry	Boys and Girls n/s		High
Cumming 2014	1351 (671, 680)	NS (11.0-13.0 y)	Predicted % adult height	Accelerometry	Boys positive	Girls n/s	High
Gammon 2017	1011 (0, 1011)	12.2 y (NS)	Pubertal development scale	Accelerometry	Boys n/a	Girls positive	High
Herman 2015	534 (286, 248)	9.6 y (9.0-10.0 y)	Pubic hair development [P]	Accelerometry	Boys positive	Girls positive	High
Lee 2016a	236 (0, 236)	13.6 y (11.0-15.0 y)	Pubertal development scale	Pedometry	Boys n/a	Girls n/s	High
Rodrigues 2010	302 (135, 167)	14.2 y (13.0-16.0 y)	Predicted % adult height	Accelerometry	Boys positive	Girls n/s	High
Vermeesch 2015†	509 (0, 509)	NS (10.0-14.0 y)	Pubertal development scale	Accelerometry	Boys n/a	Girls positive	High
Questionnaire-Measured							
Allen 2015	3956 (NS)	NS (12.0-13.0 y)	Pubertal development scale	Questionnaire	Boys and Girls positive (screen time)		Moderate

Beghin 2019†	1842 (916, 926)	16.6 y (12.5-17.4 y)	Genital development [P] Breast development [P] Pubic hair development [P]	Questionnaire	Boys positive (video games); n/s (other screens)	Girls n/s	High
Britton 2004	186 (0, 186)	9.0 y (NS)	Breast development [P] Pubic hair development [P]	Questionnaire	Boys n/a	Girls n/s	High
Brodersen 2005	4320 (2578, 1742)	11.8 y (NS)	Pubertal development scale	Questionnaire	Boys positive	Girls n/s	High
Drenowatz 2013	1118 (592-526)	7.6 y (6.3-8.9 y)	Predicted % adult height	Questionnaire	Boys positive (TV); n/s (video games)	Girls n/s	High
Lee 2017	74186 (38221, 35965)	14.9 y (13.0-18.0 y)	Age at menarche Age at spermarche	Questionnaire	Boys and Girls positive		High
Marques 2016	1324 (0, 1324)	NS (10.0-13.0 y)	Age at menarche	Questionnaire	Boys n/a	Girls positive (computer use)	High
Micklesfield 2015	381 (189, 192)	NS (11.0-15.0 y)	Genital development [P] Breast development [P]	Questionnaire	Boys positive	Girls positive	High
Murdey 2004	119 (64, 65)	NS (10.0-17.0 y)	Voice development Age at menarche Pubic hair development [S]	Questionnaire	Boys positive (but n/s after adjust sleep)	Girls positive (but n/s after adjust sleep)	Low
Murdey 2005	119 (64, 65)	NS (10.0-17.0 y)	Voice development Age at menarche Pubic hair development [S]	Questionnaire	Boys positive (weekday)	Girls n/s	Low
Page 2010	1007 (467, 540)	11.0 y (10.0-11.0 y)	Pubertal development scale	Questionnaire	Boys and Girls positive (computer, TV)		Moderate
vanJaarsveld 2007	5229 (2982, 2247)	11.8 y (NS)	Pubertal development scale	Questionnaire	Boys positive	Girls mixed results†	High
Vermeesch 2015†	509 (0, 509)	NS (10.0-14.0 y)	Pubertal development scale	Questionnaire	Boys n/a	Girls positive	High

n/a = not applicable; n/s = not significant; † = did not control for age in analysis; P = physician or nurse assessed; S = self-assessed; † = early maturing girls had greater sedentary behaviours (SB) at earlier ages and then lower SBs at later ages compared with average maturing girls

Table 5. Summary of studies that assess the relationship between maturity and sports participation or active transportation.

First Author and Year	Sample Size (Boys, Girls)	Mean Age (Range)	Maturity Assessment	Assessment	Summary of Results by Sex		Quality Score
Sports Participation							
Allen 2015	3956 (NS)	NS (12.0-13.0 y)	Pubertal development scale	Questionnaire	Boys and Girls inverse		Moderate
Barkai 2007	99 (0, 99)	15.5 y (13.0-18.0 y)	Age at menarche	Questionnaire	Boys and Girls n/s		High
Drenowatz 2013	1118 (592-526)	7.6 y (6.3-8.9 y)	Predicted % adult height	Questionnaire	Boys inverse	Girls n/s	High
Maia 2010	588 (588, 0)	NS (13.0-18.0 y)	Skeletal age	Questionnaire	Boys n/s	Girls n/a	High
Silva 2019	803 (402, 401)	12.9 y (10.0-17.0 y)	Predicted APHV	Questionnaire	Boys and Girls inverse		High
Werneck 2018a†	1152 (512, 640)	13.0 y (10.0-17.0 y)	Predicted APHV	Questionnaire	Boys n/s	Girls inverse	High
Werneck 2018b†	991 (412, 579)	13.4 y (10.0-17.0 y)	Predicted APHV	Questionnaire	Boys n/s	Girls n/s	High
Active Transportation							
Garnham-Lee 2017	611 (277, 334)	12.4 y (11.0-12.0 y)	Predicted APHV	GPS, Maps; Questionnaire	Boys n/s	Girls n/s	High

Micklesfield 2015	381 (189, 192)	NS (11.0-15.0 y)	Genital development [S] Breast development [S]	Questionnaire	Boys n/s	Girls n/s	High

n/a = not applicable; n/s = not significant; † = did not control for age in analysis; [P] = physician or nurse assessed; [S] = self-assessed